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# Experimental Study of an Air-Augmented Waterjet Propulsor

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### ABSTRACT
Compressed air can be added to the flow in a waterjet pump to increase the thrust. The gas bubbles expand as the pump mixture passes through the pressure gradient of the convergent discharge nozzle, imparting energy into the flow. In this experiment, air is injected into a pump fitted to a model boat and static thrust is measured for a range of void fractions using two nozzles. Air is injected between the rotor and stator and downstream of the stator stage. Measurements of the pump and air flow rates, thrust, pressures, and torque show how the injected air affects thrust, pump head rise and power. Results show that the thrust can be increased by 12%, and the pump operates at a lower flow coefficient and higher headrise. The energy balance shows that thrust can be increased with less shaft power than required for the same thrust increase using higher pump speed, but the energy required for the air injection offsets the savings in shaft power.

### Keywords
Waterjet, two-phase flows, thrust boost, air-augmentation

## 1 INTRODUCTION

### 1.1 Concept
Underwater jet propulsion using compressed gas is a concept that has been tested or modeled in various forms for over fifty years (Mottard & Shoemaker 1961). The basic principle involves gas bubbles expanding and exerting pressure-volume work on the surrounding water as the bubbles travel through the pressure gradient in a nozzle. The simplest version of this propulsor is a ramjet in which air is mixed into the high stagnation pressure behind a diverging inlet, and the compressed gas accelerates the mixture out the contracting nozzle in the back. Such propulsors are simple and lightweight, having no moving parts, and are not limited by cavitation. The extensive work of Gany (2008) and Mor & Gany (2007) have focused on this concept and produced a working prototype.

An extension of this concept is the gas-augmented waterjet, in which gas is injected downstream of a waterjet pump and upstream of a flow-accelerating nozzle. This waterjet variation, relative to the simple ramjet, should have a higher power density and better acceleration performance, but it lacks the simplicity of the ramjet because it still involves a shaft-driven pump. The gas-augmented waterjet has the potential advantage of increased power density without increased weight, not accounting for the addition of a compressor in the hull. Gas augmentation could also be used to add thrust boost capacity for an existing waterjet, allowing the main waterjet to be smaller and possibly more efficient for normal operations. Even if the efficiency is not as high as the primary propulsor, a thrust-augmenting device might be an attractive alternative to increasing the primary pump size for short-duration peak thrust requirements. Application of boost thrust might include over-coming the added resistance for transitioning to planning mode on a planning boat, for example.

### 1.2 Previous work
Early works on two-phase jets focused on energy transfer from the gas to water phase and the resulting forces in nozzle flows. Tangren et al (1949) modeled homogenous mixed flows, and Witte (1969) developed solutions for mixed flows with separate phases, allowing unequal velocities, pressures, and temperatures. Recently, Gowing et al (2010) measured the efficiency of the energy exchange from two phase flows in different nozzles and showed efficiencies up to 70%. The one-dimensional flow equations were used by Amos et al (1973) to predict the performance of air-augmented waterjets, and Stansell et al (1976) extended the analysis to include a gas turbine powerplant and the effect of extracting compressed gas from various turbine stages. Thrust augmentation was predicted to be higher for higher craft speeds and higher pump flowrates. Tsai et al (2005) presented an experimental evaluation of a waterjet ski with an added air injection system. The maximum thrust augmentation was about 10% for a bollards condition, but close to 100% for the highest speed and void fraction (0.5). Gany et al (2008) showed thrust increases of 25% to 50% with an air-augmented waterjet ski, and the results matched predictions assuming energy transfer efficiencies

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14. ABSTRACT

**Compressed air can be added to the flow in a waterjet pump to increase the thrust. The gas bubbles expand as the pump mixture passes through the pressure gradient of the convergent discharge nozzle, imparting energy into the flow. In this experiment, air is injected into a pump fitted to a model boat and static thrust is measured for a range of void fractions using two nozzles. Air is injected between the rotor and stator and downstream of the stator stage. Measurements of the pump and air flow rates, thrust, pressures, and torque show how the injected air affects thrust, pump head rise and power. Results show that the thrust can be increased by 12%, and the pump operates at a lower flow coefficient and higher headrise. The energy balance shows that thrust can be increased with less shaft power than required for the same thrust increase using higher pump speed, but the energy required for the air injection offsets the savings in shaft power.**

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of about 70%. These thrust benefits were measured in a bollards condition and the nozzles were adjusted for the different engine speeds tested. In these jet ski tests, the effects of the air injection on the performance of the primary pump, shaft power, and overall energy budget were not measured. This study was intended to explore those effects as well as measure thrust augmentation.

## 2 EXPERIMENT

### 2.1 Boat and pump model

A 0.8 m wide by 0.3 m deep by 4 m long portable fishing boat was fitted with a waterjet pump and tested in a bollards condition, attached to a fixture through a force gage. The boat (Ron Chapman Shipwrights, LA) had a flat bottom and transom to accommodate a mixed-flow waterjet pump with an upstream rotor and downstream stator. The pump inlet blended smoothly with the boat bottom and the discharge was above the water level. Figure 1 shows the boat and pump together. The pump was made of transparent resin using sintered laser prototyping. This made visualization of the flow possible and allowed creation of air passages in the pump body. The pump dimensions were modified to accommodate two different size nozzles fitted with two different air injection schemes, for a total of four configurations. The injection schemes are discussed briefly.

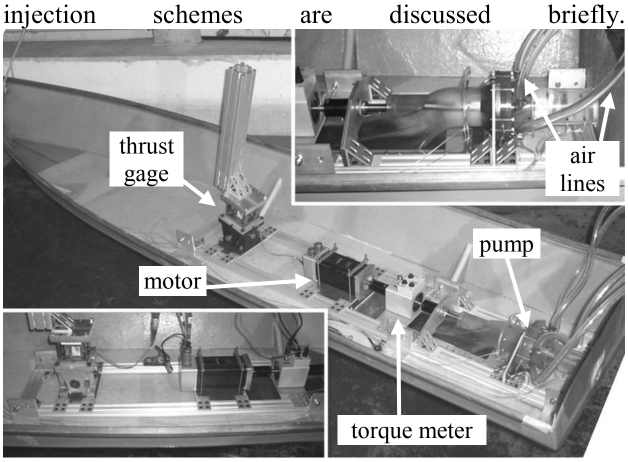


**Figure 1: Boat and pump**

### 2.2 Injector and nozzle design

The first scheme injected air through 6 mm ports between the pump rotor and stator, with the ports located midway between the stator vane leading edges. Injecting air at this location would maximize mixing through the stator stage but possibly alter the stator performance from its fully-wetted design point. The ports were simple holes and should have created relatively large bubbles. Figure 2 shows the ports close up.

The other injection scheme used both a centerbody and annular sintered metal injector located aft of the stator. The large surface area of these injectors was designed to maintain small bubble generation at high air flowrates. Injection at this location would preserve the fully wetted pump performance but possibly suffer from poor bubble mixing. Air was connected to the centerbody injector through hollow vanes that held the centerbody at the downstream end. Figure 3 shows the injector details. For sizing the nozzles, two criteria were used. One nozzle had the same discharge area (21.7 $cm^2$) as the original pump design, and the second nozzle was made larger (29.8 $cm^2$) to accommodate the increased flowrate of the two phase flow. The nozzles were fitted with pressure taps and made to be interchangeable with the different injection schemes.

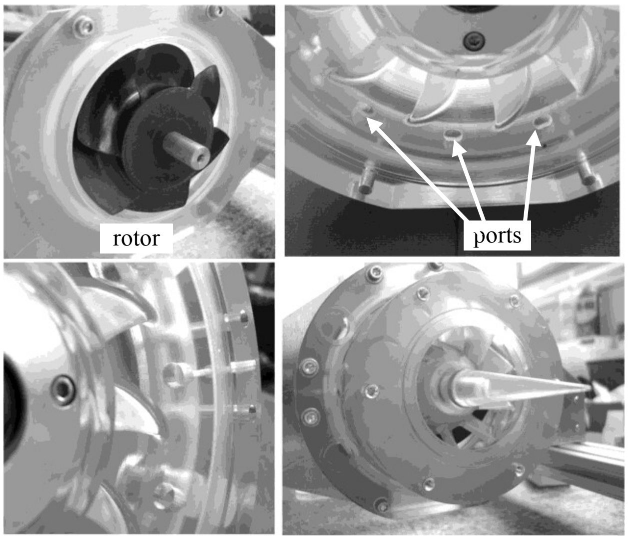


**Figure 2: Rotor/stator injection assembly**

### 2.3 Motor, air systems and instrumentation

The pump was driven by a 3,000 rpm, 2.3 kW motor with feedback speed control, and it controlled speed to within 1 rpm of the desired value. Rotor torque was measured with a non-contact, strain-gaged torque meter. Air was supplied from a 3.8 kW compressor with a maximum discharge pressure of 1 bar at 1330 lpm flow. The flowrate was measured with an orifice meter made to ASME specifications using 1D and 1/2D pressure tap locations. To avoid putting loads into the model, the air supply connected to the pump through 4–6 flexible plastic tubes that hung vertically from above the model.

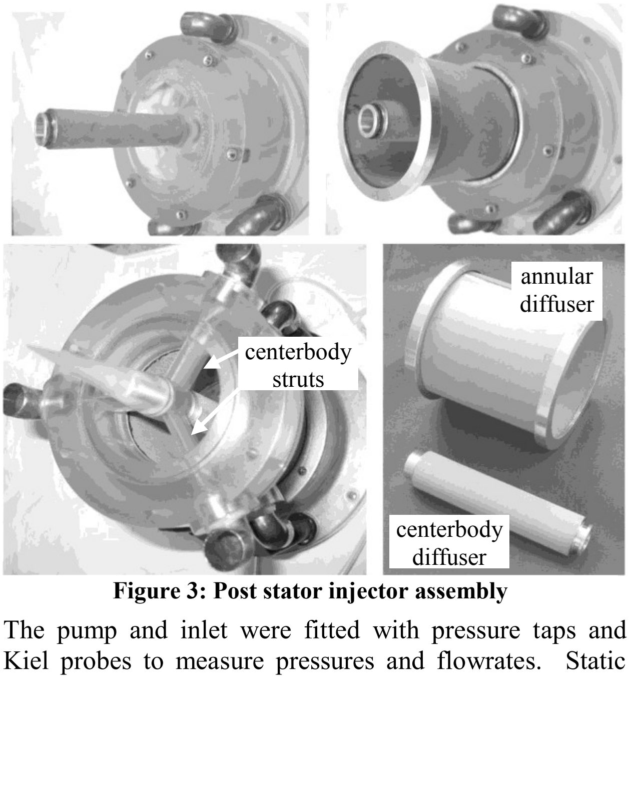


**Figure 3: Post stator injector assembly**

The pump and inlet were fitted with pressure taps and Kiel probes to measure pressures and flowrates. Static

wall taps and Kiel probes were installed in the parallel section of the inlet just upstream of the rotor and used to measure inflow velocity changes with air injection. The pump flowrate was calculated from the fully-wetted bollards thrust measurement, assuming a uniform discharge velocity profile,

$$V = \sqrt{T/\rho A} \quad \text{and} \quad Q = VA \tag{1}$$

Changes of that flowrate with air injection were calculated as the ratio of the inlet velocity normalized on its value with no air injection,

$$Q_{W\,air\_inj} = Q_{W\,no\_air}\left( Vi_{air\_inj} / Vi_{no\_air} \right) \tag{2}$$

Figure 4 shows the Kiel probe arrangement in the inlet. Static taps were also located between the rotor and stator to measure the rotor headrise.

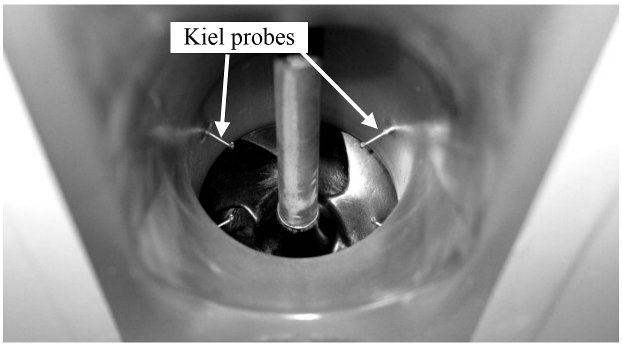


**Figure 4: Kiel probes in inlet**

The variable reluctance pressure transducers measured differential pressures and all the data were collected through a laptop computer using LabView software. The pressure taps connected to the pump and nozzle at mid-level, but the tap internal geometry and tubes were made at a slight downward angle to prevent air from getting into the lines.

### 2.3 Test procedure

The pump was run at a low speed and primed by pushing the back end of the model down, and then the pressure tap lines were purged of air by forcing water from a pressure tank through the system. The pump was brought to speed, and data were recorded for the water-only condition. The air system was started with its discharge flowing through a bypass valve. Then the valve to the model was opened and the flowrate adjusted using both the valve to the model and the bypass valve. Data were recorded for a range of flowrates, up to the maximum value. This maximum was the point at which the pressure of the injected air exceeded the pump pressure at the injection point, and the air ventilated the upstream rotor and caused the pump to lose its prime.

## 3 RESULTS

The pump was run over a range of speeds without air injection to insure consistent performance over a range of speeds. Figure 5 shows the pump efficiency (flux of total discharge head divided by shaft power) for the water-only case. The pump efficiency becomes flatter at speeds above 1800 rpm, so tests were conducted at two higher speeds to be less sensitive to Reynolds effects. Note that the efficiency is lower for the pump configured with the post-stator injector because of the added frictional losses of the walls and centerbody struts. The efficiency is also higher for the small design nozzle than the large one. The resulting nozzle speeds ranged from about 5 m/s to 10 m/s.

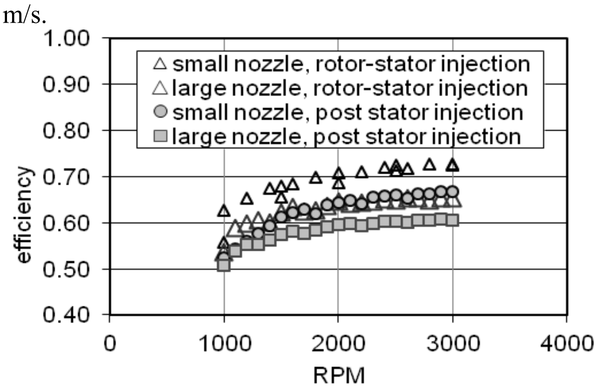


**Figure 5: Water-only rotor efficiency**

### 3.1 Rotor/stator injection results

First, the results are examined for the case of air injected between the rotor and stator. Figure 6 shows the thrust and torque, normalized on their water-only values, as a function of injected air void fraction. The void fraction is the ratio of the volume air flow to the volume mixture flow at standard conditions,

$$VF = Q_{air} / \left( Q_{air} + Q_{water} \right) \tag{3}$$

For the small nozzle, the thrust changes little, but the large nozzle shows a thrust increase up to 12%. The water flowrate, derived from the inlet probes, decreases with air injection for both nozzles as shown in Figure 7 (flowrate is normalized on the water-only flowrate). The decrease is directly proportional to void fraction. Figure 8 shows the corresponding increase in rotor pressure rise, again normalized on the water-only value. The large nozzle causes the rotor headrise to increase more rapidly than when configured with the small nozzle. Hence, the injected air affects the pump operating point by reducing the flow and increasing the rotor headrise.

This change in the pump condition is shown in Figure 9 as the pump efficiency variation with the non-dimensional flow coefficient. The pump efficiency is defined using only the rotor pressure rise,

$$\eta = Q_{water} \Delta P_{rotor} / 2\pi n \Gamma \tag{4}$$

in which n is shaft speed, Γ is the rotor torque and the flow coefficient is

$$\Phi = Q_{water} / \left( nD^3 \right) \tag{5}$$

in which D is the rotor diameter. For the same nozzle, the lower speed (rpm) curves fall below the higher speed ones because of the Reynolds effects, as shown in Figure 5. For the large nozzle, the water-only flow coefficient is

greater than the region of peak efficiency, and the reduction of flow caused by the injected air brings the pump closer to its peak efficiency point. For the small nozzle, the range of flow coefficients that encompass the injected air data are near the peak values. This explains the principle difference between the nozzles' results: with the large nozzle, the air injection reduces the flow of the pump to a more efficient operating point, but for the small nozzle, the operating point changes little compared to the zone of peak efficiency.

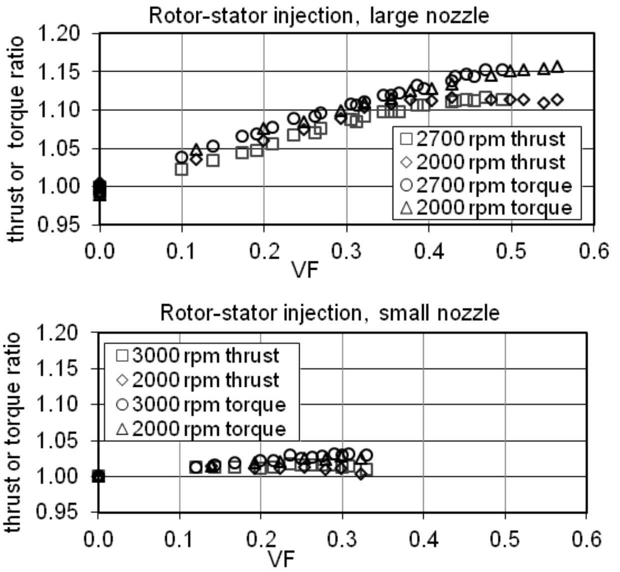


**Figure 6: Rotor-stator injection effects on thrust and torque**

For both nozzles, the rotor power changes in a fashion similar to the thrust, as shown in Figure 6. In spite of the 12% thrust increase for the large nozzle, the shaft power increases up to 15%, while for the small nozzle, the thrust and power changes are a few percent at most.

It is interesting to look at the increase of power required for increased thrust. For the large nozzle, Figure 10 shows the power required for a range of thrust with and without air injection. If only pump power is considered, the solid line shows that the increase in power for going from 176 Nts thrust to 195 Nts thrust is 0.18 kw without air injection, but only 0.14 kw with air injection. But if the power of the air flux is added to the pump power, 0.49 kw more is needed to accomplish this thrust augmentation with air injection. Hence, air injection can augment thrust with reduced pump shaft power, but the added power required for the air delivery is significant.

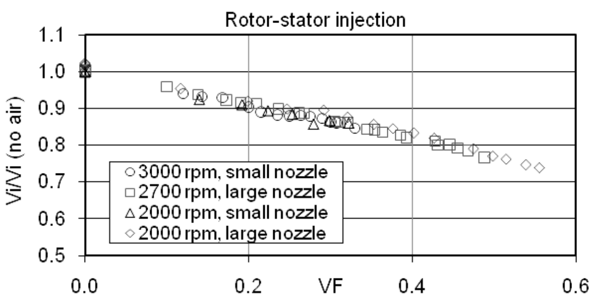


**Figure 7: Rotor-stator injection effects on pump flowrate**

### 3.2 Post-stator injection results

The results for the post-stator injection scheme are similar to the rotor-stator injection. Figure 11 shows the air injection effects on thrust and torque for the two nozzles. The results are similar whether injecting through the inner, centerbody or outer, annulus injector. Only the high speed cases are shown for clarity. For the large nozzle, the thrust increases about 3% but the torque (rotor power) increases up to 15% with air injection. For the small nozzle, the thrust actually decreases in spite of an increase in torque. The changes in flowrate and rotor headrise are almost identical for this injection scheme compared to the rotor-stator injection and the graphs are left out for clarity. However, the pump efficiency effects are different.

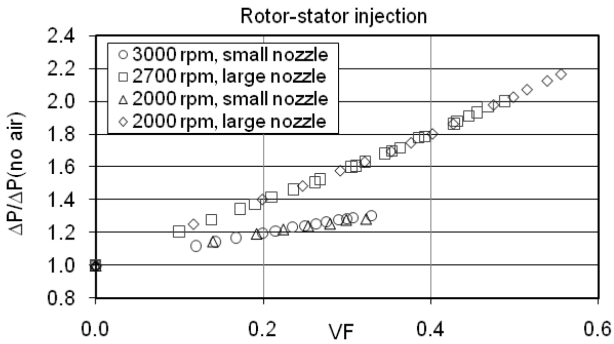


**Figure 8: Rotor-stator injection effects on rotor headrise**

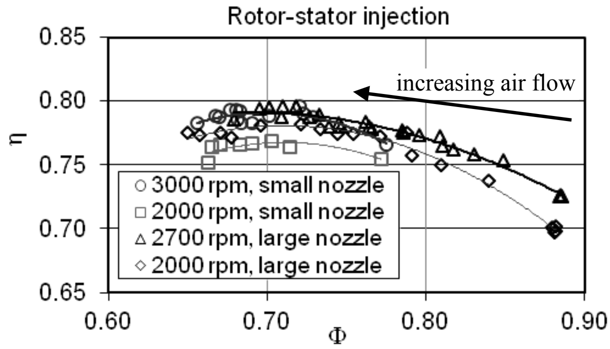


**Figure 9: Pump (rotor headrise) efficiency vs flowrate**

Figure 12 shows the rotor efficiency as a function of flow coefficient. For the large nozzle, the coefficients change with air injection over the region of peak efficiency, but for the small nozzle, the flow is reduced below the peak values and the rotor efficiency falls off. This is believed to cause the thrust decrease seen for the small nozzle.

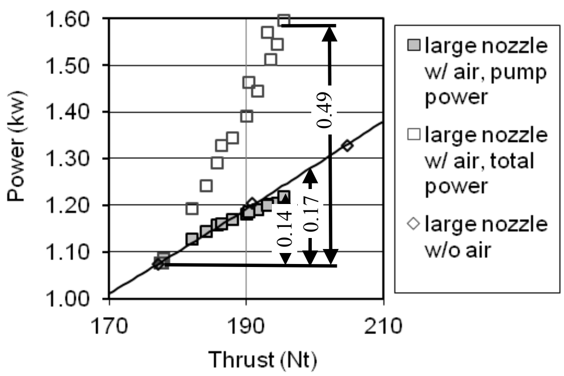


**Figure 10: Power for different thrust modes**

In summary, the present data show a maximum 12% thrust increase with an enlarged nozzle at 35% void fraction, comparable with the 10% increase measured by Tsai et al (2005) at 50% void fraction. The thrust increases of up to 50% measured by Gany et al (2008) involved adjustments of the nozzle for different pump speeds. It appears that the thrust increase is improved by modifying the nozzle to accommodate the air injection. The results of Tsai (2005) also show significant thrust increase with forward speed, and supports the prediction of the mathematical flow models (Tangren et al 1949), (Witte 1969).

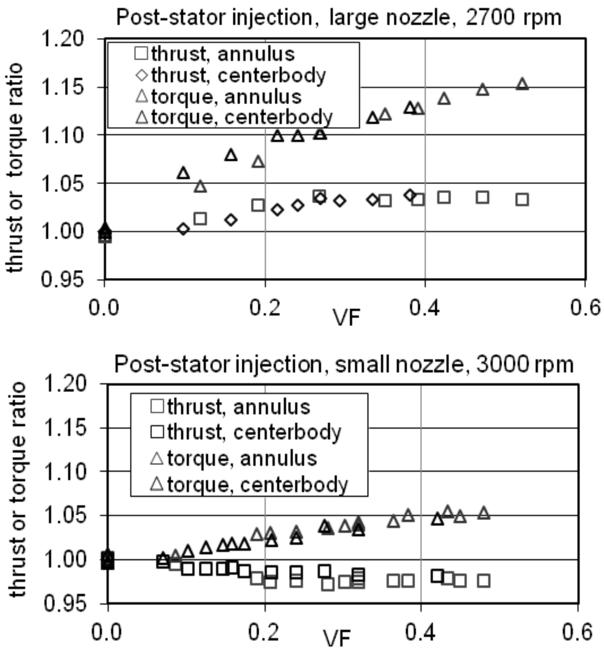


**Figure 11: Post stator injection effects on thrust and torque**

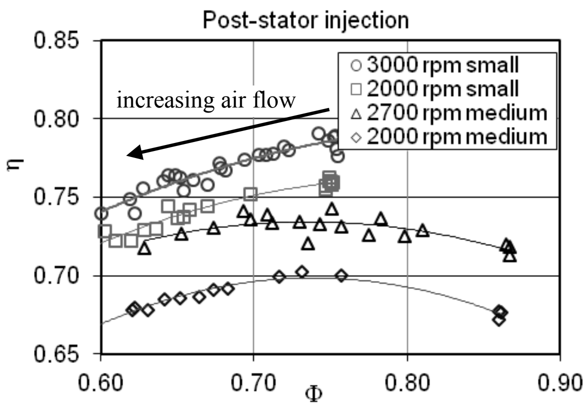


**Figure 12: Post-stator injection effects on efficiency**

## 4 CONCLUSIONS

It is possible to increase the thrust of a waterjet propulsor by air injection but the injection can strongly affect the primary pump performance. The injection process can reduce the pump flow, increase its headrise, and affect the pump efficiency. These pump interactions can have as much effect on the thrust as the air augmentation process itself. The sensitivity of the pump to injection may depend on the pump design, however. The nozzle size must be increased from its water-only design point to allow thrust augmentation by injection. Using injection, the thrust can be increased using less rotor shaft power than can be achieved by higher pump speed alone. But the power required for the injected air is significant and the total power required for thrust augmentation is more than if the rotor speed is simply increased.

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